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AUTOMATED STRAIN GAUGE PLETHYSMOGRAPH

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

May 1993

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

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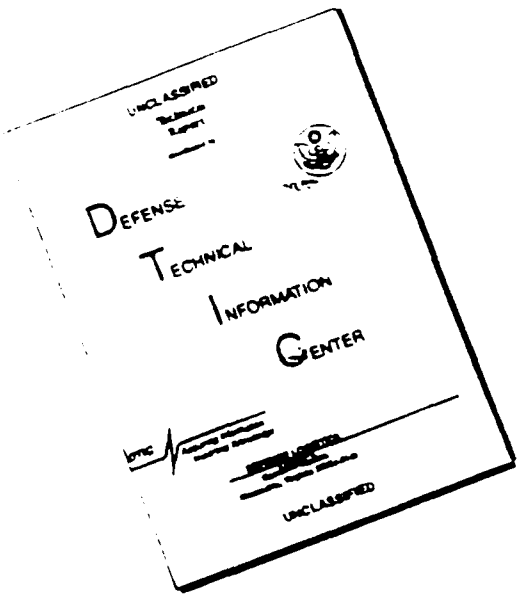

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TECHNICAL REPORT

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AUTOMATED STRAIN GAUGE PLETHYSMOGRAPH

by

Tammy J. Doherty, Lou A. Stephenson, Margaret A. Kolka, Gary N. Sexton,
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May 1993

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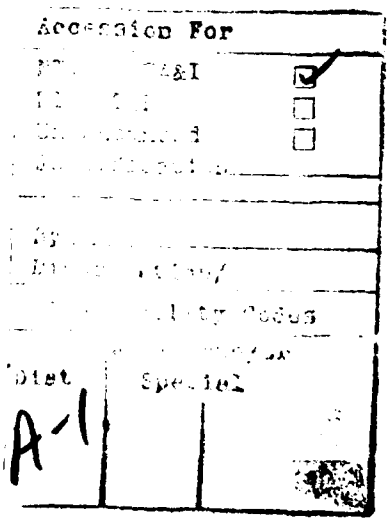

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13. ABSTRACT *(Maximum 200 words)*

This report describes a microcomputer-controlled system which measures limb blood flow by strain gauge plethysmography. Hardware components include a suitable microcomputer, compatible data acquisition unit, Hokanson EC-4 plethysmograph, pneumatic cuff inflation system, and a relay/switching unit for remote calibration of the plethysmograph unit and inflation of the pneumatic cuffs. The software developed for use with this system enables automatic electronic calibration of the plethysmograph prior to each measure of limb blood flow, collection and storage of limb volume records at user-specified time intervals, interpretation of limb volume records, and calculation of rates of limb blood flow. To validate this system, we compared forearm blood flows estimated using the automated system with forearm blood flows estimated using a conventional (Whitney) hardware configuration that uses millivolt strip chart recordings. Correlation between blood flows measured in the right arm (automated system with 12-second distal occlusion) with blood flows estimated in the left arm (manual system with prolonged distal occlusion) were generally good. We conclude from these studies that the automated system is an authentic alternative to manual collection systems and that 12-second periods of distal occlusion is sufficient for stable records of limb blood flow.

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FOREWORD

Skin blood flow is a critical indicator of the thermodynamic state of an individual. Venous occlusion plethysmography is a non-invasive method used to estimate skin blood flow. Venous (but not arterial) blood flow is occluded at a proximal site on the limb (i.e., upper arm or thigh). The rate of change of limb volume, measured using either a strain-gauge or volume plethysmograph immediately following venous occlusion, is presumed to measure limb arterial blood flow. Since muscle blood flow is assumed constant in a non-active limb, changes in limb blood flow measured using venous occlusion plethysmography are attributed to changes in skin blood flow.

In the literature, numerous variations of the venous occlusion plethysmography technique are described. These variations differ with respect to the type of plethysmograph, the protocol for venous occlusion and release of the occlusion, the addition of distal arterial and venous occlusion in some cases, and the methods used to interpret records of limb volume change. Many aspects of the venous occlusion plethysmography system in use in the Environmental Physiology and Medicine Directorate at USARIEM are unique. This report describes the methods and procedures developed and regularly used at USARIEM and compares blood flows measured using the USARIEM system with blood flows measured in the opposite limb of the same subject using a more conventional system. These studies were done in order to validate the venous occlusion technique after computer automation of conventional procedures that employed strip chart recordings. The purpose in writing this report is to document the USARIEM system as well as to enable other researchers to more easily interpret blood flows measured at this laboratory.

ACKNOWLEDGEMENTS

This work would not have been possible without the volunteers who participated in the validation tests for the automated strain gauge plethysmograph described in this report. We wish to thank them for their time, effort, and perseverance.

We thank Drs. L.D. Carlson, C.B. Wenger and E.R. Nadel who taught us the conventional venous occlusion plethysmography technique as it was used in their research.

EXECUTIVE SUMMARY

This report describes a microcomputer-controlled system which measures limb blood flow by strain gauge plethysmography. Hardware components include a suitable microcomputer, compatible data acquisition unit, Hokanson EC-4 plethysmograph, pneumatic cuff inflation system, and a relay/switching unit for remote calibration of the plethysmograph unit and inflation of the pneumatic cuffs. The software developed for use with this system enables automatic electronic calibration of the plethysmograph prior to each measure of limb blood flow, collection and storage of limb volume records at user-specified time intervals, interpretation of limb volume records, and calculation of rates of limb blood flow. To validate this system, we compared forearm blood flows estimated using the automated system with forearm blood flows using a conventional (Whitney) hardware configuration that uses millivolt strip chart recordings. To enhance the range of expected skin blood flows, test subjects exercised at 60% of their maximum oxygen uptake. Five subjects participated in this study with individual correlations ranging from R^2=0.12 to R^2=0.92. Lack of a good correlation in one subject appeared to be associated with a narrow range of estimated blood flows for that subject. A second test was performed to validate our use of a 12-second period of distal arterial and venous blood flow occlusion (as opposed to prolonged distal arterial flow occlusion). Again, blood flows were estimated in opposite forearms of human test subjects. Correlation between blood flows measured in the right arm (automated system with 12-second distal occlusion) with blood flows estimated in the left arm (manual system with prolonged distal occlusion) were generally good. Six subjects participated in this test with R^2 values ranging between 0.61 and 0.95. We conclude from these studies that the automated system is an authentic alternative to manual collection systems. It was confirmed that interpretation of limb volume records and the use of 12-second periods of distal occlusion is sufficient for stable records of limb blood flow.

INTRODUCTION

The volume plethysmograph, combined with the venous occlusion procedure, has been used successfully to measure rates of limb blood flow (Hewlett and van Zwaluwenberg, 1909). In this method, the limb segment under investigation is placed in a rigid, fluid-filled, sealed enclosure so that increases in limb volume cause a corresponding fluid displacement which is measured by a volume recorder. Venous blood flow is occluded at a proximal site on the limb (i.e., upper arm or thigh). The rate of limb volume change, measured using the volume plethysmograph immediately following the venous occlusion, is presumed to measure limb arterial blood flow. In an inactive limb, changes in limb blood flow are usually attributed to changes in skin blood flow. For this reason, this system is often used in studies of temperature regulation. The usefulness of this system is limited however, because the apparatus severely restricts the movement of the limb under investigation, and requires minimal movement of the specific limb and adjacent body segments. In addition, placement of skin-surface probes to measure temperature, skin wettedness, local sweating rates, or conductive heat loss is virtually impossible with this system.

Whitney, 1953, was the first to introduce a viable alternative to measuring limb volume directly. He showed a direct relationship between the rate of limb volume increase and the rate of limb girth increase as measured by resistance changes in a mercury-in-rubber strain gauge placed around the limb. Compared to the volume plethysmograph, the strain gauge is small, light-weight, nonirritating to the test subject, and allows free translational movement of the limb. In addition, the gauge covers only a small area on the skin, allowing placement of other skin surface probes on the same limb. The strain gauge plethysmograph has been shown to be as reliable as the volume plethysmograph in measuring limb blood flow (Burger *et al.*, 1959; Clarke *et al.*, 1957, 1958; Whitney, 1953). For these reasons, the strain gauge plethysmograph has become the method of choice for limb blood flow measurements.

Strain gauge plethysmography systems in use today differ only slightly from the one described by Whitney in 1953. In a simple system, strain gauge resistance is measured with a Wheatstone bridge (Whitney, 1953) and output to a strip chart recorder. More advanced systems use electronic plethysmograph units that may be calibrated electronically by a small switch on the console. In general, calibrations are performed pre- and post-experiment in both types of systems. Because calibration can be affected by limb position, gauge placement, and gain adjustments on the plethysmograph, it is preferable to calibrate the system *in situ*, prior to each blood flow measurement. This paper describes an automated system capable of automatically calibrating the plethysmograph prior to each limb blood flow measurement, controlling pneumatic cuff inflation, and recording limb volume changes.

Whether the electrical output from a strain gauge is sent to a strip chart or a separate computer, a final interpretation of limb volume records is usually performed manually. The investigator selects an interval of the limb volume record, then computes the rate of change of limb volume (slope or tangent) over that interval. A single experiment may require hundreds of these interpretations. This paper additionally describes computer software to automate this process.

The use of a distal blood flow occlusion cuff varies from one laboratory to another (Johnson *et al.*, 1974; Roberts and Wenger, 1980; Wenger *et al.*, 1975). Distal occlusion (the occlusion of arterial blood flow at a site distal from the strain gauge, such as the wrist or ankle) is used to partition aberrant back flow from the distal site which could confound arterial blood flow measurements in the intended limb (Grant and Pearson, 1938). Upon inflation of the distal pneumatic cuff, limb volume increases then decreases sharply, returning to an intermediate level after about one minute (Kerslake, 1949). Because of this instability in initial limb volume, most researchers suggest taking blood flow measurements after at least one-minute of distal cuff inflation (Clarke *et al.*, 1958; Greenfield *et al.*, 1963; Johnson *et al.*, 1974; Kerslake, 1949; Roberts and Wenger, 1980; Wenger *et al.*, 1975). In our experience, however, prolonged distal occlusion is uncomfortable and may cause the test subject

duress, increased catecholamine release and other factors which could affect limb blood flow. A shorter distal occlusion period of 15 seconds has been suggested (Grant and Pearson, 1938). However, this shorter time interval includes the blood flow transients and could lead to errors in blood flow estimation. In this paper, we compare forearm blood flows measured using a 12-second distal occlusion protocol, with forearm blood flows measured in opposite forearms using a continuous distal occlusion protocol.

STATEMENT OF PURPOSE

This study was designed to compare an automated method for the measurement of forearm blood flow using venous occlusion plethysmography with a classical "Whitney" configuration. In addition, we compared different lengths of time for the arterial occlusion of the hand before forearm blood flow measurements were made. Finally, we showed that software calculations of forearm blood flow were as accurate as hand calculations with the additional benefit of preventing investigator bias.

METHODS

HARDWARE

Both the automated and conventional systems in this study use a 4-wire mercury-in-silastic strain gauge to measure changes in limb girth. In the conventional manual system, gauge resistance is measured using a Wheatstone bridge (Whitney, 1953) and output to a strip chart recorder. In the automated system, the 4-wire gauge lead connects to the front of a modified Hokanson EC-4 plethysmograph (Hokanson *et al.*, 1975). Our modification was to mount a small relay inside the plethysmograph in parallel with the 1% electrical calibration switch (Fig. 5; Hokanson *et al.*, 1975) to enable external triggering of the calibration switch from a remote site or computer. Output from the plethysmograph is sent to a Hewlett-Packard 3421A data acquisition/control unit. Two surge tanks (Bi-Tronics model BI-111) inflate the proximal and distal occlusion cuffs to preselected pressures. Inflation and deflation of the cuffs are controlled by electrical solenoid valves which can be switched either manually or electrically from a remote site. For the automated system, a relay/switching unit was designed and equipped with a 5-volt DC power supply to drive the remote switches for the surge tanks and plethysmograph calibration. Three of the channels on the HP-3421A have been configured as actuators to control cuff inflation and plethysmograph calibration. A Hewlett-Packard model 87 desktop computer controls the HP-3421A and houses the software for measurement, storage, and analysis of limb volume data. A schematic of the electrical device for the control of cuff inflation and automatic calibration of the plethysmograph is shown in Figure 1.

LIMB VOLUME MEASUREMENTS

The sequence of events for limb blood flow measurement begins with the inflation of the distal occlusion cuff to a super-systolic pressure (usually 200-220 Torr, 27-29 kPa). Twelve seconds after inflation of the distal collusion cuff, the proximal venous occlusion cuff is inflated to approximately 50 Torr. Strain

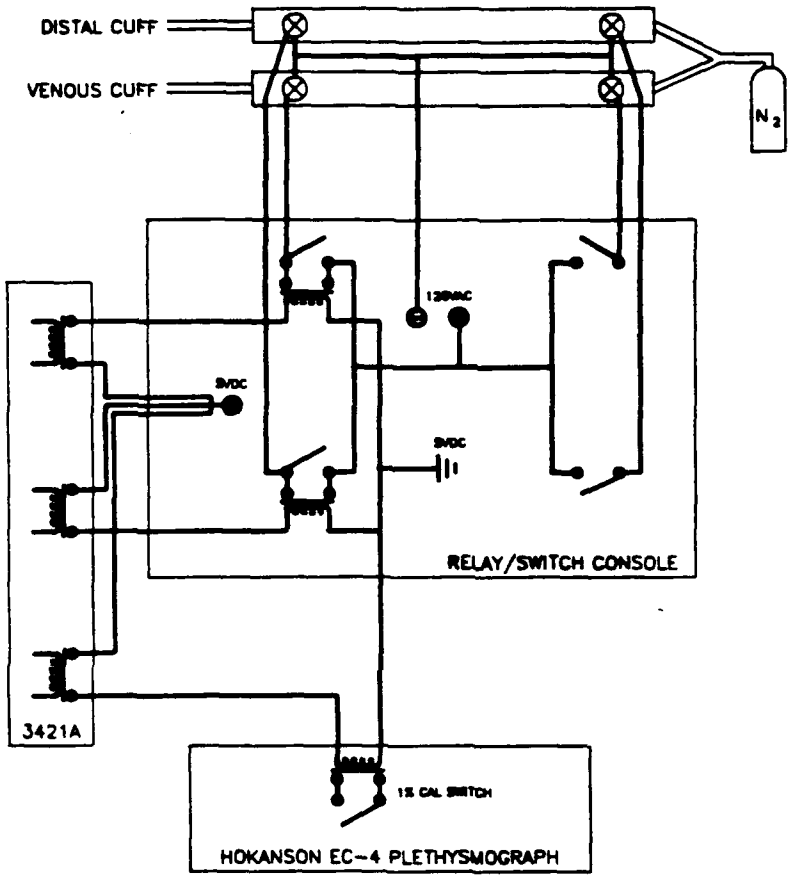

Figure 1. Schematic for cuff inflation control and automatic calibration of the plethysmograph.

gauge resistance is measured either by the Wheatstone bridge or the EC-4 plethysmograph device and output to either a strip chart recorder or data acquisition system. At the end of this 10-second period, both occlusion cuffs are deflated.

In the original conventional system, calibrations are performed pre- and post-experiment and the surge tanks are triggered manually. In the automated system, the surge tanks are under computer control and are triggered at the appropriate times. Calibrations are performed automatically, ten seconds after inflation of the distal occlusion cuff. Calibration consists of reading a baseline voltage from the plethysmograph, triggering the 1% calibration switch, and reading the resulting voltage. The system gain is calculated by dividing the 1% increase in resistance by the measured change in voltage. The calibration process is performed three times and the median value of the three gains is used as the calibration factor for the subsequent limb volume measurements.

BLOOD FLOW ESTIMATION

The interpretation of limb volume records is based on suggestions originally given by Whitney, 1953. Sample plots of forearm volume over a 20-second sampling interval are shown in Figures 2 through 5. In all cases, the initial rate of arterial inflow is represented by the slope of the tangent line. In Figure 2, the rate of volume change is consistent and the entire 20-second interval is used to determine the slope of the tangent line. In Figure 3, the curve levels off after approximately five seconds, indicating that venous pressure exceeds venous cuff pressure, and that venous blood is exiting the forearm. In this case, only the initial, higher slope, is used to determine the rate of arterial inflow. Figure 4 shows a curve exhibiting a movement artifact due to involuntary limb muscle tension which sometimes occurs during inflation of the venous cuff. In this case, the normal-looking curve following the aberrant measurements is used to determine the slope of the tangent line. Curves of the type in Figure 5 indicate that, upon inflation of the venous cuff, blood is delayed in reaching the strain gauge. This type of curve indicates that the limb joint between the venous occlusion cuff and the strain gauge (e.g., the elbow or knee) is flexed too far,

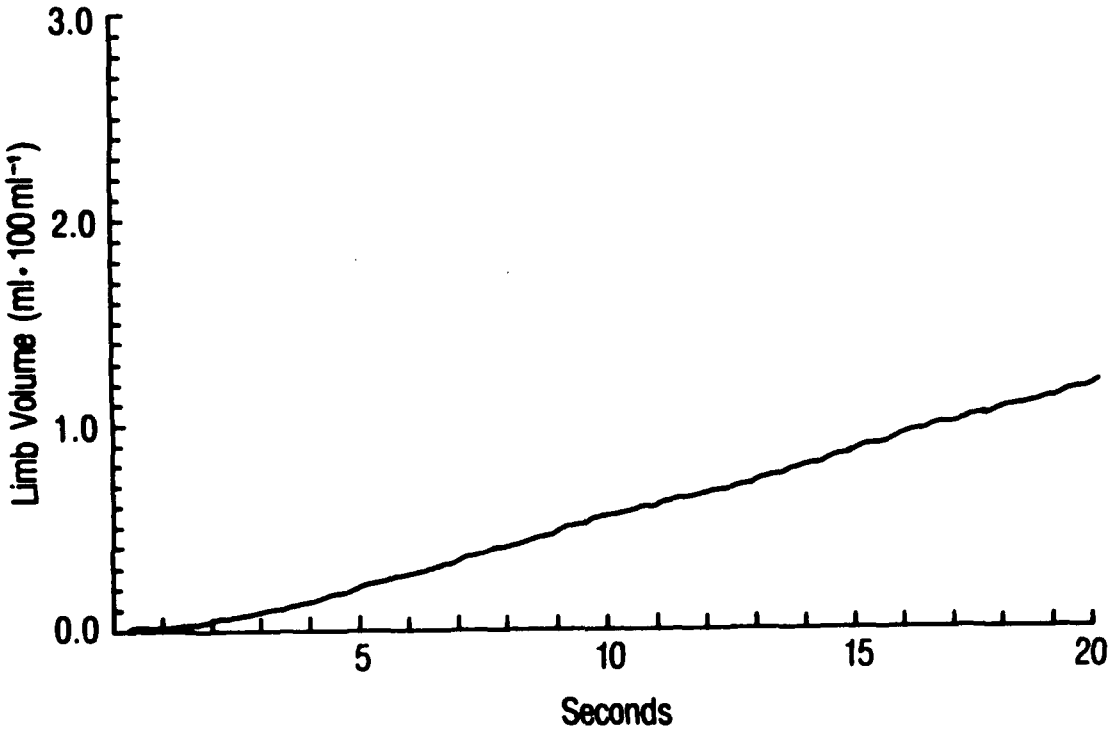

Figure 2. Typical record of limb volume in which the rate of change of limb volume, over the entire 20-second interval, is used to compute limb blood flow.

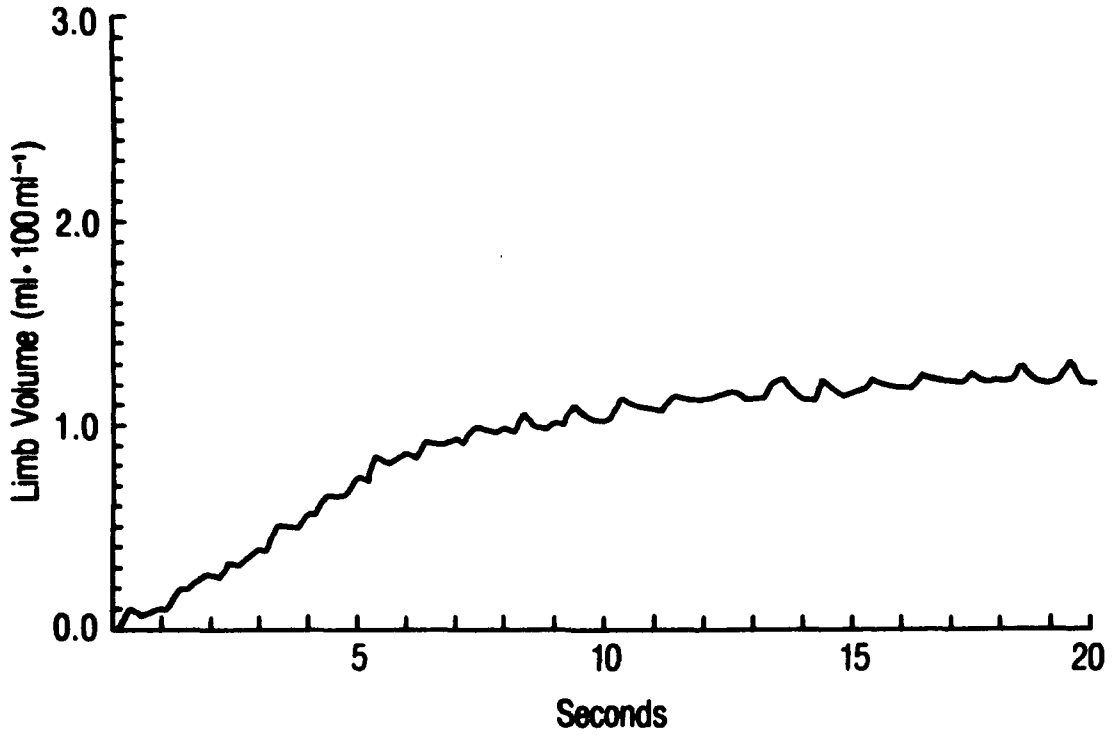

Figure 3. Record of limb volume showing an inflection in the curve at approximately 5.4 seconds. This inflection or "break point" corresponds to the point at which venous pressure exceeds venous cuff pressure and blood escapes the limb. The rate of change of limb volume, up to the inflection, is used to compute limb blood flow.

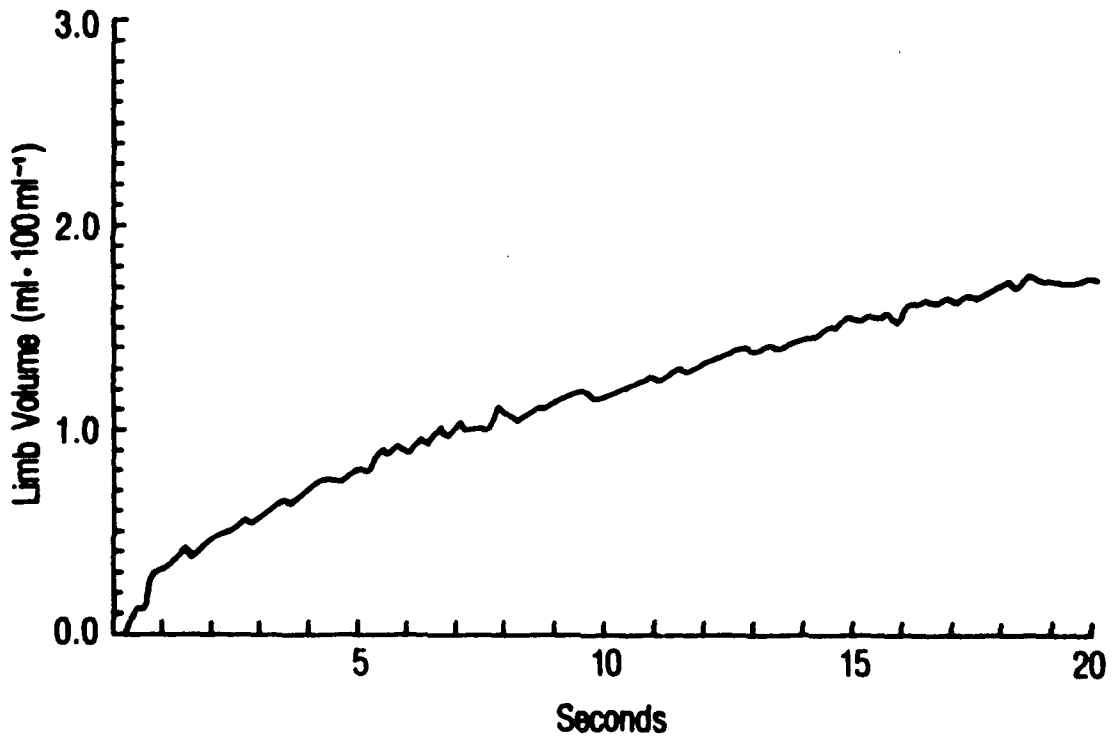

Figure 4. Record of limb volume showing an initial, rapid increase in limb volume followed by a slower increase after about 1 second. The initial increase may occur due to involuntary limb muscle tension/contraction during or immediately following venous cuff inflation. The rate of change of limb volume following the initial increase is used to compute limb blood flow.

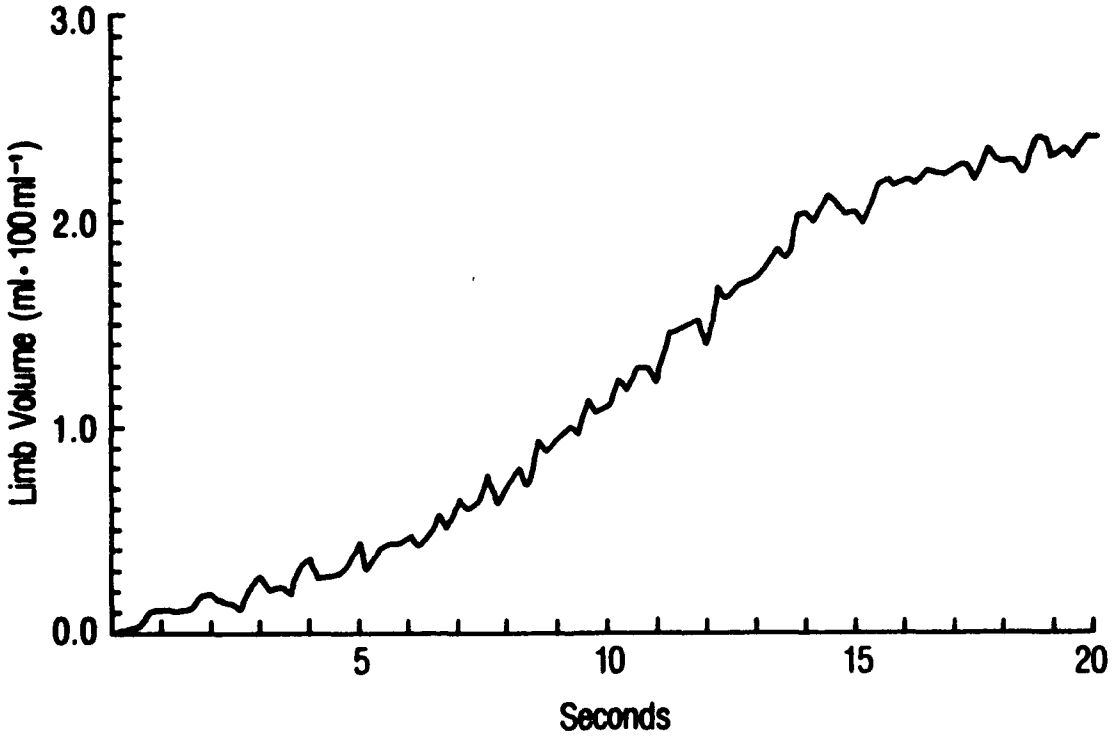

Figure 5. Record of limb volume showing an exponential-type increase in limb volume. This delayed limb volume increase is presumably due to a delay in blood reaching the limb at the location of the strain gauge. This problem might occur when a limb joint between the venous cuff and the strain gauge is over-flexed. No interpretation of this type of curve is possible.

partially restricting arterial blood flow. According to Greenfield et al., 1963, there is no way to properly interpret such a curve.

In the conventional manual system, the investigator determines which data intervals are suitable for blood flow estimation, determines the slope of the limb volume curve over that interval, and adjusts this slope based on pre- and post-experimental calibration factors. In the automated system, a computer program resident in the data acquisition system is used to interpret records of limb volume measures. The data are smoothed using a 4-2 median technique (Vellamann and Hoaglin, 1981). Location of a possible inflection point (the point at which venous pressure exceeds venous cuff pressure) is based on slope differences between the data points prior to a potential inflection point (P) and the data points after P. To speed up the process, the slope of each one-second interval following the last zero or negative reading is calculated using least-squares regression. Following this calculation, the mean of the one-second-slopes prior to P and the mean of the one-second-slopes after P are compared. The inflection point, corresponding to the largest difference between one-second-slope means is used as the initial end-point for the interval. If the percent difference between the two mean slopes is less than 25%, then the end-point is set to 10-seconds (the last recorded point). If the inflection point occurs prior to 3 seconds, which indicates a clear movement artifact (Figure 4), the starting point is set to P and a new inflection point, between P and the 10-second point, is determined. If the mean slope of the first group is less than the mean slope of the second group, indicating a plot similar to that in Figure 5, the interval from P to the 10-second point is used in an attempt to salvage the data. The investigator must decide whether the curve should be discarded. Plots of limb volume over the 10-second interval, with appropriate computer-generated intervals and slopes, are presented to the investigator. The investigator is allowed to review these plots and select different endpoints for regression. Slopes for these user-selected intervals are calculated by the computer using linear least-squares regression. Rates of blood flow are computed from the rates of limb volume change and stored on diskette for subsequent analyses.

EXPERIMENTAL VALIDATION

Two series of experiments were conducted to validate the hardware and software components of the present system. Skin blood flow in both forearms of 6 subjects (2 males; 4 females) seated in a supine position on a modified sled-cycle ergometer (Bigland-Ritchie *et al.*, 1973) at T_a = 30°C were compared. Measurements were made at rest and frequently during exercise to elicit a wide range of blood flows for each subject.

A padded sling was tied about the wrist of each arm and suspended from two supporting positions. The distance and orientation of the sling relative to the two positions was selected to allow the arm to be extended (thereby keeping arterial flow open) and raised to heart level (ensuring proper venous return). This suspension system, as compared to a one-point suspension system (Johnson *et al.*, 1974), was found to reduce muscle tension and irregularities in the strain gauge curve due to respiration (Rowell, 1983; Wenger *et al.*, 1975). In addition, this suspension system also appears to reduce incidence of artifact due to proximal cuff inflation (Figure 4).

Pressure cuffs were placed around the wrist and upper arm, occluding blood flow to-and-from the hand and venous return from the forearm. The strain gauges were placed symmetrically on the lower forearm, distal to the belly of the forearm musculature. Esophageal temperature (T_{es}) and skin temperatures (T_{sk}) on the medial ventral surface of the forearms were also measured.

After establishing that calculated forearm blood flows were laterally symmetrical (unpublished observations), differences between manual (right arm) and automated (left arm) systems were tested. In the conventional manual system, the strain gauge resistance was measured with a Wheatstone bridge (Whitney, 1953) and the electrical output was transferred directly to a strip chart recorder. All interpretation of strain gauge curves was made by a trained investigator. In both arms, distal occlusion cuff inflation was intermittent, with 12 seconds from distal cuff inflation to proximal cuff inflation, and cuff deflation 10 seconds after proximal cuff inflation. A second experiment compared blood

flows measured following a short period (12 seconds) of distal blood flow occlusion (left arm) with blood flows measured in the opposite forearm in which prolonged distal cuff inflation was used (right arm). The distal pneumatic cuff on the right arm (manual system) remained inflated throughout the experiment except for brief periods (approximately one minute) at the request of the test subject. Collection of limb volume data and interpretation of limb volume records was accomplished with the automated system on the left arm and manual system on the right.

STATISTICAL ANALYSES

Comparisons between left and right arm blood flows for each experiment were quantified using linear least squares regression analysis. A statistical regression model was used on data derived from blood flow values measured using the new automated system (left arm) and blood flow values measured using the manual plethysmograph system (right arm). An accounting was made for the thermal effect on local blood flow due to differences in local skin temperature between right and left arms.

RESULTS AND DISCUSSION

Results of regression analyses for the first experiment are provided in Table 1. In general, inclusion of local skin temperature differences in the regression model did not significantly reduce the unexplained variance. Therefore, the regression model includes left arm blood flow (measured using the automated system with 12-second distal occlusion) as the dependent variable, and right arm blood flow (measured using the manual system with 12-second distal occlusion) as the independent variable. Correlation coefficients for individual subjects ranged from 0.35 to 0.96. Except for the 0.35 value, all other r-values exceed 0.76. Although the correlations were not as high as we originally expected, the overall variability in blood flow measurements from one instant to the next was relatively high and might explain some of the discontinuity between right and left arm blood flows. Review of the regression coefficients and residuals indicates that blood flows measured using the automated system were not consistently higher or lower than blood flows measured using the manual system. From these results, we can conclude that microcomputer data capture and interpretation of strain gauge records produces statistically equivalent results (calculated blood flows) as those produced by the more tedious and time-consuming manual interpretation of strip-chart recordings.

Results of regression analyses for the second experiment, are provided in Table 2. Again, local skin temperature differences were excluded from the regression model because such inclusion did not significantly reduce the level of unexplained variance. The regression model includes left arm blood flow (measured using the automated system with 12-second distal occlusion) as the dependent variable, and right arm blood flow (measured using the manual system with continuous distal occlusion) as the independent variable. Correlation coefficients for individual subjects ranged from 0.78 to 0.97. Correlations were not as high as we originally expected, but again are explained by the general variability in blood flow measurements from one instant to the next. Blood flows measured using the automated system were not consistently higher or lower than blood flows measured using the manual

system. We conclude that 12-second distal occlusion is equivalent to continuous distal occlusion as far as blood flow measurements are concerned.

The results of this study confirm the validity of the automated strain gauge plethysmography system presently in use at this laboratory. This is equivalent, analytically to the conventional manual technique. The advantages of the automated system are obvious. In addition to freeing laboratory personnel who would normally attend to the plethysmograph during an experiment, the automated system (with a 12-second distal occlusion period) enables measurement of blood flow at intervals of 30 seconds, fast interpretation of limb volume records, and storage of blood flow data in files along with other cardiovascular and thermoregulatory variables. Additionally, calibration of the strain gauge system prior to blood flow measurements enhances the reproducibility of limb blood flow measurements. Finally, validation of the 12-second distal occlusion period allows us to eliminate the possibly confounding effects of test subject duress, associated with prolonged distal blood flow occlusion, on limb blood flow measurements.

Table 1. Regression analysis for the first experiment comparing forearm blood flows measured using the automated (FBF_A) and manual (FBF_M) systems with 12-second distal blood flow occlusion. Inclusion of skin temperature differences did not reduce the level of unexplained variance. Therefore, the final regression model may be expressed by: $FBF_A = \beta_0 + \beta_1 FBF_M$, units are $ml \cdot 100ml^{-1} \cdot min^{-1}$.

subject	n	β_0	β_1	R^2
2F	41	-2.60	1.45	0.89
3F	40	-1.38	1.51	0.92
4F	42	1.12	0.57	0.60
1M	46	0.52	0.65	0.58
2M	45	3.42	0.27	0.12

Table 2. Regression analysis for the second experiment comparing forearm blood flows measured using the automated system with 12-second distal blood flow occlusion (FBF_{12}) and using the manual system with prolonged distal occlusion (FBF_{∞}). Inclusion of skin temperature differences did not reduce the level of unexplained variance in the regression model. Therefore, the final regression model may be expressed by: $FBF_{12} = \beta_0 + \beta_1 FBF_{\infty}$, units are $ml \cdot 100ml^{-1} \cdot min^{-1}$.

subject	n	β_0	β_1	R^2
1F	45	-1.19	1.41	0.78
2F	46	-0.26	0.88	0.91
3F	43	-3.18	1.89	0.95
4F	39	-0.64	0.70	0.61
1M	45	-0.09	1.06	0.87
2M	45	1.27	0.43	0.77

CONCLUSIONS

An automated strain gauge plethysmography system is described and validated. This system provides estimations of forearm blood flow which are equivalent to estimations produced by a conventional, non-automated system. We showed that continuous or prolonged distal blood flow occlusion is not necessary and validated our use of a 12-second pre-measurement period of distal (wrist) occlusion for the measurement of forearm blood flow. This system is routinely used in experiments supporting Science and Technology Objective 3T: Environmental Injury - Demonstrate the Efficacy of Strategies to Predict, Prevent and Treat Environmental Illnesses, Injuries and Performance Decrements; specifically Task A "Identify mechanisms controlling skin blood flow for the purposes of thermoregulation in man: impact of neuronal, hormonal and endothelial factors in regional cutaneous vasodilation" in the Environmental Physiology and Medicine Directorate.

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